DOCUMENT RESUME

ED 116 617 IR 002 483

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TITLE	An Interactive, Interdisciplinary, On-Line Graphics System for Presenting and Manipulating Directed Graphs.
INSTITUTION	Texas Univ., Austin. Project C-BE.
SPONS AGENCY	National Science Foundation, Washington, D.C.
REPORT NO	EP-24-1-8-74
PUB DATE	8 Jan 74
NOTE	23p.; For related documents see IR 002 463 and 464
EDRS PRICE	MF-$0.76 HC-$1.58 Plus Postage
DESCRIPTORS	*Computer Graphics; Computer Programs; Computers; *Display Systems; Educational Technology; Engineering; *Engineering Education; Engineering Technology; *Input Output Devices; Linguistics; On Line Systems; Program Descriptions
IDENTIFIERS	Digraphs; Intelligent Terminals; *Project C BE

ABSTRACT

An interactive graphics system has been implemented for tutorial purposes and for research in man-machine communication of structural digraphs. An IMLAC intelligent terminal with ligthpen input is used in conjunction with a NOVA minicomputer. Successful application in linguistics and engineering problem solving are discussed, the latter in detail. (Author/EMH)

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ED116617

AN INTERACTIVE, INTERDISCIPLINARY, ON-LINE GRAPHICS SYSTEM FOR PRESENTING AND MANIPULATING DIRECTED GRAPHS

EP-24/1/8/74

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IR 002 483

This study was supported by Project C-BE under Grant GY-9340 "The Use of Computer-Based Teaching Techniques in Undergraduate Science and Engineering Education," from the National Science Foundation to The University of Texas at Austin, Drs. John J. Allan and J.J. Lagowski, Co-Directors.

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ABSTRACT

An interactive graphics system has been implemented for tutorial purposes and for research in man-machine communication of structural digraphs. An IMLAC intelligent terminal with lightpen input is used in conjunction with a NOVA minicomputer. Successful applications in linguistics and engineering problem solving will be discussed, the latter one in detail.

AN INTERACTIVE, INTERDISCIPLINARY, ON-LINE GRAPHICS SYSTEM FOR PRESENTING AND MANIPULATING DIRECTING GRAPHS

An interactive graphics system has been implemented in a classroom and laboratory environment for tutorial purposes and for research in man-machine communication of structural digraphs. The approach arises out of the need to measure human specification of structure among options that are more complex than his sequential communicating activities. The measurement of these structural messages is aided considerably by viewing them as directed graphs, allowing the application of a large body of developed theory. The detection of these directed graphs is straightforward and the evaluation of a particular structure for the satisfaction of particular rules or the determination of equivalence to a desired answer may be then considered a graph isomorphism problem.

For example, if a set of possible steps that a subject might take in the solution of a problem is presented as possible nodes for a graph, then how the subject selects and connects those nodes into a graph of a solution is an indicator of how the subject sees structure in the problem and its solution. Alternatively, in academic subjects where structure is well defined, (i.e., transformational grammar) the learning of this structure can be based on detecting and measurement of student-created graphs. In these examples, the order in which the steps are actually performed provides useful information to evaluate understanding of a problem.

Using a NOVA minicomputer and an IMLAC interactive graphics terminal with lightpen input, routines have been developed which permit the creation and editing of directed graphs as displayed on an intelligent graphics terminal. The prime responsibility of the NOVA minicomputer in this system is updating an adjacency matrix containing information about the nature of the digraph nodes and their connectedness, and the issuing of drawing instructions to the IMLAC terminal. The prime responsibilities of the IMLAC are maintenance of the display and detection of lightpen commands. A routine that checks a subject-created graph against a desired graph makes possible feedback in a learning task.

The content-independent nature of graph theory makes the concept of such a system highly transferrable among disciplines. It is now being used in teaching information structure and problem solving strategies in Engineering Design, and transformational grammar in Linguistics.

A third area of application concerns research on presentation of non-linguistic data (spatial information on graphics displays) and the effect of non-linguistic response modes (light pen input in graphics systems). The system is also being considered for other applications.

This particular type of computer graphics system, with its unusual capability for structural communication, detection, and measurement, allows the expansion of human research into complex communication problems.

In order to detect and to measure the man-machine communication of structure, a system of programs has been developed in Data General Extended BASIC. In this paper the parent system, the system for manipulating directed graphs, and the use of this system as applied to engineering design will be discussed.

The Parent NOVA-IMLAC CBERT BASIC Interactive Graphics System.

The host computer system on which the routines of interest were developed has a unique set of advantages and disadvantages in the experimental-educational environment. The central theme of the NOVA-IMLAC system is the use of an intelligent, vector-capable, interactive graphics terminal as an extremely sensitive interface to a relatively inexpensive minicomputer-disk configuration running Extended BASIC.

This results in a master-slave relation between the NOVA minicomputer and the IMLAC graphics terminal in which the NOVA bears the burden of data manipulation. A heavy emphasis on data manipulation in the IMLAC terminal would have decreased the chances of transferring the routines to another system at a later date. As the amount of data manipulation at the intelligent terminal increases, the need for a graphics-oriented specialized configuration increases. As a result, the probability of adapting the developed software for another system would decrease.

Another advantage of the C-BE NOVA/IMLAC System is that the NOVA minicomputer communicates with the IMLAC terminals through BASIC CALLS

to machine language subroutines leaving BASIC unchanged in syntax. The use of the developed software for the IMLAC requires, then, only the writing of the interface subroutines at a particular site. Also, during development, the software efforts for the NOVA and the IMLAC were begun and continued semi-independently with a minimum of revision when the combined parent system became operational.

The LOGOS executive is the resident software for the IMLAC graphics minicomputer. It was designed and written to take full advantage of the long-vector capability, lightpen, and push-down subroutine stack features of the IMLAC minicomputer. LOGOS (see Speaker, 1973) (Level-Oriented Graphics Operating System) permits the multiple use of a single set of drawing instructions, and, as a result, a single graphical item (such as a circle) can appear hundreds of times on the graphics screen by using LOGOS subroutine calls. In addition, each of these graph item appearances can be made to return a unique pair of parameters when detected by the lightpen.

This lightpen capability is not limited just to graphical items. Also displayed letters or words (verbal displays composed of user-definable characters) can be sensitive to detection by the lightpen and return a pair of values.

A tracking cross can be positioned on the screen, and the raster values of the X-Y location can be requested allowing graphical data entry to a

limited degree. This is entirely adequate where a point in space is to be communicated, or for similar tasks.

The result is a flexible interactive graphic display capability in a resident, but easily interfaced, executive. In experimental or educational tasks, a subject's responses can take the form of a character, a word, a sentence, a point, a line, an arc, or any arbitrary composite of drawing instructions. This is all in addition to plotting and alpha-numeric display and editing capabilities.

In summary, the C-BE NOVA/iMLAC/LOGOS interactive graphics system is designed to minimize the hardware-dependent aspects of graphics interaction while maximizing the graphics interface capabilities and sensitivity. It represents a favorable combination of flexibility, transferability, and cost.

The System for Creating and Manipulating Directed Graphs.

An assumption is made that activities specific to engineering design are the specification of partitions on options (possible parameters, designs, calculations, etc.), and the specification of a topology on those options (layout, sequence, phasing, system definition, etc.). (Beazley and Allan, 1973b) With this assumption in mind, then the detection and measurement of design activities for research or educational purposes requires a communication medium sensitive to these activities. The solution chosen is a graph-theoretic data structure represented to the subject as a directed graph.

Harary (1969) has advocated the use of directed graphs as a representation of the structure of a set of components in a network. These components can be anything from various parts of speech, options in a design, probabilities of certain events, individuals in a group, etc. In addition, there is a set of ordered pairs specified on those nodes which, together with the set of nodes, specifies the structure or topology of these nodes. In some kinds of problems one can specify weightings and/or attributes with both the nodes and the ordered pairs. In set theoretic notation, this is:

A = Set of Nodes

B = Set of Ordered Pairs

C = Set of Node Attributes

D = Set of Ordered Pair Attributes

$$B = \{<X,Y> : (X \varepsilon A)\ (Y \varepsilon A)\}$$

$$C = \{\ c: (c \varepsilon C)\ (<c,x> \varepsilon M)\ (X \varepsilon A)\}$$

$$D = \{\ d: (d \varepsilon D)\ (<d, <x,y>> \varepsilon N)\ (<x,y> \varepsilon B)\}$$

By no means is this way of communicating structure limited to that already described but the system discussed is constrained for practical reasons as described above. With each node there is associated an attribute number, a parameter which defines what kind of option that node represents. Since it is possible to select an option more than one time for use, another number, a unique number, is associated with each node as it is chosen.

The set of ordered pairs specified on the set of nodes can be represented in matrix form as an adjacency matrix. It is specified as follows:

$$a_{ij} = 0 \quad \text{IF } (< i, j > \notin B)$$
$$a_{ij} = 1 \quad \text{IF } (< i, j > \varepsilon B)$$

The adjacency matrix is constructed according to the unique number. Thus the system is capable of creating the adjacency matrix of any network of nodes of any attribute to any degree of redundancy within the hardware space limitations of the host NOVA-IMLAC system.

For a more detailed discussion of the properties of adjacency matrices, see Harary (1969).

In the classroom, application difficulties arise with respect to available technology for use. Pedagogically, it is not only desirable to record the directed graph created by the student, but also to compare it to a desired graph. Or, one might want to see if certain organizational rules are obeyed (rules established by theoretical or empirical considerations). It was decided that at the present level of understanding of design behavior it would be counter-productive to attempt to specify lawful relationships among the various nodes. Instead, classroom tutorials are based on the learning of instructor-created diagraphs. This requires an algorithm that can compare a student-created digraph with the instructor-created digraph and determine whether they are the same.

Again, the pedagogical approach of using directed graphs benefits directly from existing technology. A student-created graph will be

structurally the same as the instructor-created graph if they are isomorphic. This presents an immediate problem in the case where nodes are redundant with respect to attributes. It may not be possible to quickly distinguish between nodes which have the same attributes and similar or identical interconnections with other nodes of the graph.

The decision was made to delimit instructor-created digraphs to digraphs without attribute redundancy. The comparison routine became a simple matter of ordering the student-created matrix according to the arrangement of attributes of the instructor-created matrix and performing a subtraction. Execution time on the NOVA-IMLAC system for the directed graph of 15 nodes is less than 2 seconds in the single-user case, an entirely acceptable delay for this complex application. In addition, the remainder of the matrix subtraction furnishes valuable information about the closeness of the student attempt to create the desired graph. The zero result indicates equivalence; the non-zero result gives information about presence of unwanted connections and the absence of desired connections. This can serve as feedback to the student and data for evaluation.

In the ways described above, the designer, student, and experimental subject can be measured in an accurate, controllable way for research and pedagogical purposes. Subject to certain constraints, a digraph can be compared to a target digraph, allowing for the use of tutorial tasks for teaching subject matter or for studying patterns of learning.

Representing the Directed Graph to the Creating Individual.

Any directed graph can be specified by the set of nodes and the set of ordered pairs of first and last points. Displaying this to the individual using the graphical system is an important consideration, as these representations to the designer or student can influence, bias, or otherwise distort his behavior in the task. Here, the graphical representation of the directed graph will be discussed in detail, and discussion of the possible ergonomic factors involved in the design of the display will await results of research now in progress.

In discussing the display of the graph to the subject, consider the subject confronting the blank display. (Figure 1)
Creation of the digraph, how it is edited, and the appearance of the feedback information during a learning task will be discussed.

In its present form, the set of options, etc., are displayed at the right of the IMLAC graphics screen as a menu of verbal phrases inside of circles or squares (light buttons). Each of these phrases is sensitized for the lightpen. At the bottom of the screen are additional one-word comments like, "END," "LINK," and "DELETE." These are commands used for creating, editing, and requesting checks on the directed graphs. To create a graph, the tracking cross is positioned on the screen and the desired option chosen with the lightpen. Then the chosen option appears on the screen at the location of the cross. (Figure 2)

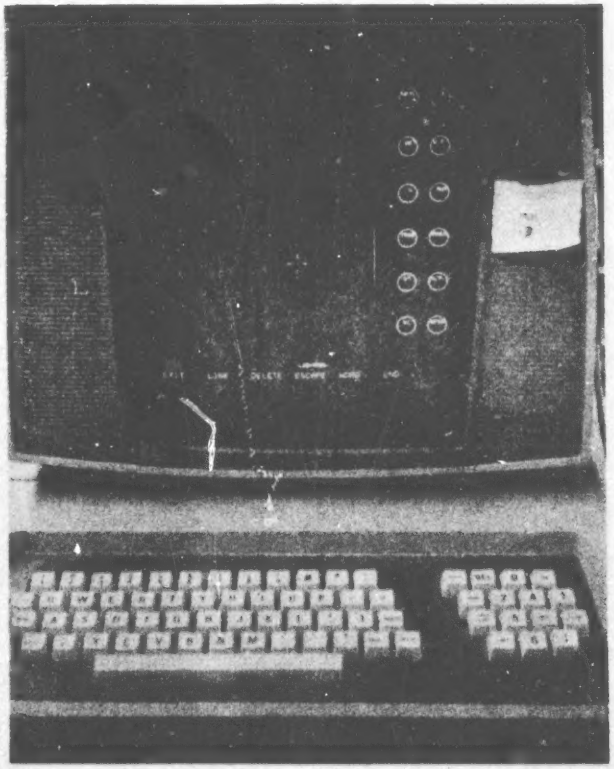

FIGURE 1

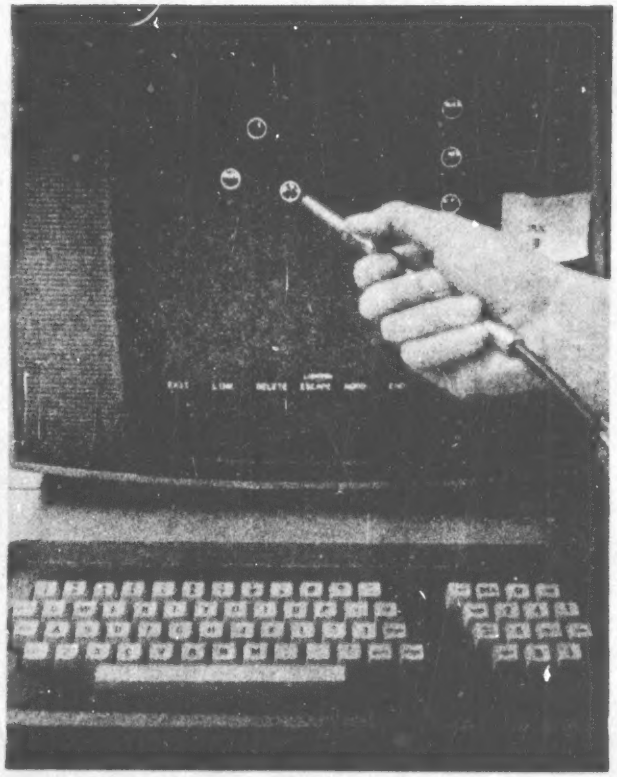

FIGURE 2

FIGURE 3

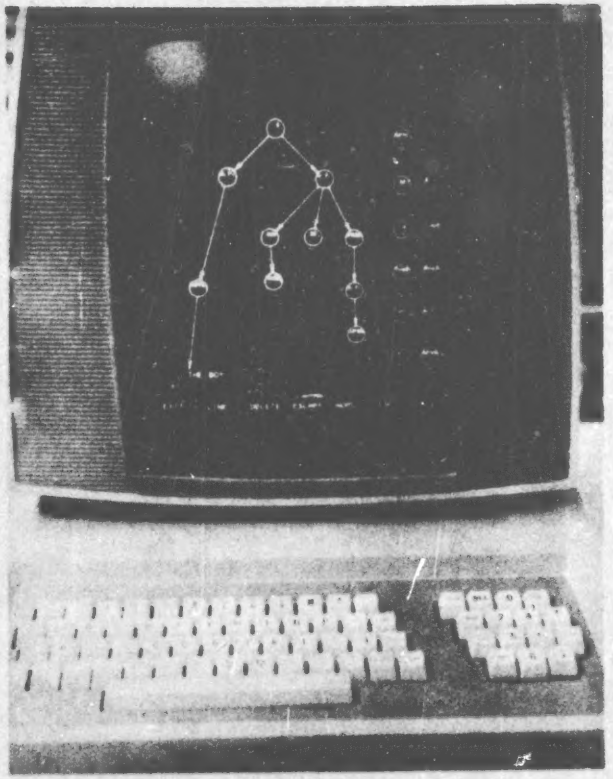

FIGURE 4

When an appropriate number (at least two) of options are assembled on the screen, the subject can link the options in a desired way by using the lightpen to select the "LINK" instruction at the base of the screen. Then the subject indicates the first and last nodes with the lightpen and an arrow appears on the screen confirming his choice. (Figures 3)

Should it be desired to edit the graph, the subject merely hits the instruction marked "DELETE" and hits the node or line to be removed.

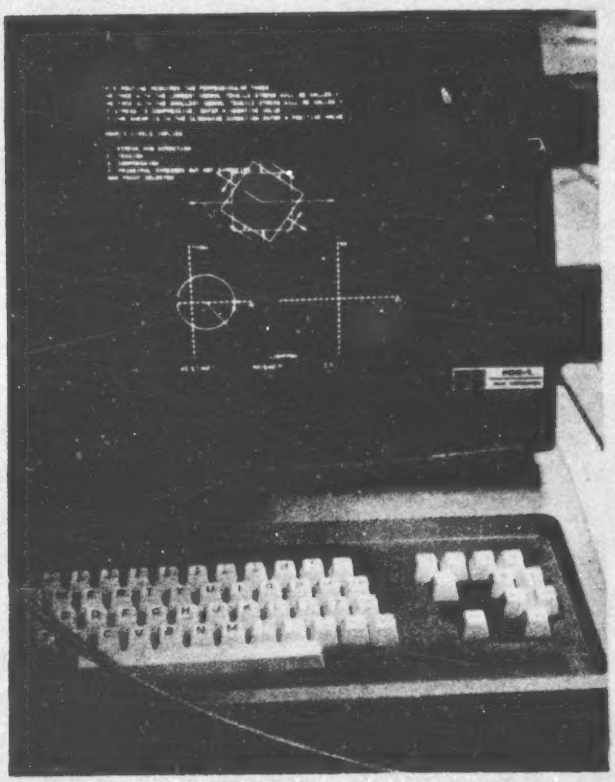

FIGURE 5

The connection or node disappears and, in the case of a node, all connections to it disappear also.

During this creation and editing of the pictorial representation of the directed graph on the graphics interface, the NOVA/BASIC main program accounts for the additions and deletions of nodes and connections by updating the adjacency matrix that corresponds to the graph. At the end of a creation session the subject hits a lightbutton labeled "END" and the adjacency matrix is copied on a file along with important secondary information (like location on the screen, special names used for referencing nodes and connections in the IMLAC terminal). At this point, the main program can chain to any other desired routine. (Figure 4).

In the situation where the routines are being used for subject training in a learning task, the next routine in the chain is the one that compares the subject-created graph to a predetermined response graph. A matrix is formed which represents an adjacency matrix of the difference between the created and desired matrices, and this is also copied on a file.

This difference matrix is read by an interpretation-feedback subroutine which either indicates success, (solid connections), blinks erroreous connections, and draws in missing ones as dotted connections. This kind of spatial feedback is possible because of the capability of the system in detecting and interpreting the created directed graphs.

The applications of system features described so far are not specific to any particular discipline. Rather, they can be applied to the measurement

of any behavior with identifiable aspects that are unique and a structure described by ordered pairs. Examples of such behavior include the specification of sentence structure according to a transformational grammar (Linguistics), specification of group structure (Social Psychology), specification of material flow (Operations Research), specification of managerial authority (Business Administration), and the specification of design information flow (Engineering Design). The general nature of the approach and the widespread impact of its content-independent technology make the system described highly transferable at the conceptual level.

The System Applied to Engineering Design Education.

The system described so far has been applied to design education in engineering, linguistics education, and for research in man-machine communication. The essential theme of these applications is the communication of structure to a machine. The discussion that follows will focus on the application to engineering design education.

The goal of the present effort is to measure performance of designers during the solution of real design problems. Such a measurement system requires that designers select from options available to them and specify a structure or structures among those options. Thus, engineering design involves choice from and the specification of relationships among options in the environment. This set of options is represented to the student as a menu. This menu is composed of possible parameters, activities, data,

and other information relevant to a particular problem. Although the repertoire of options is specified by the instructor for each instructional task, an expanded data base could make the number and types of retrievable options entirely arbitrary. A solution to an engineering problem presented to the student is embodied in the creation of the directed graph representing the systematic method of the intended solution.

Thus, the education of the embryo designer involves two components: the education of the student of the options available in the environment and the training of the student in the use of those options. Figure 5 shows a student interacting with a CAI routine on the use of Mohr's Circle for finding the principal stresses associated with biaxial stress. This is an example of the 1st component of the learning process. The method of Mohr's Circle is one of the options he will be required to use later in the stress analysis of designs under load. A set of questions about the method is answered by the graphical data entry of the stress states and the lightpen selection of different points around the circle. For each point selected, the corresponding stress element is drawn by this tutorial. The student designer becomes acaquainted with the parameters, methods and other options available for use in engineering design.

The second aspect of the education of the designer, the training of the designer in strategies of problem solving, is more complex. Figure 6 shows a typical graph that the student would be asked to learn. It indicates information flow in a solution to the following problem.

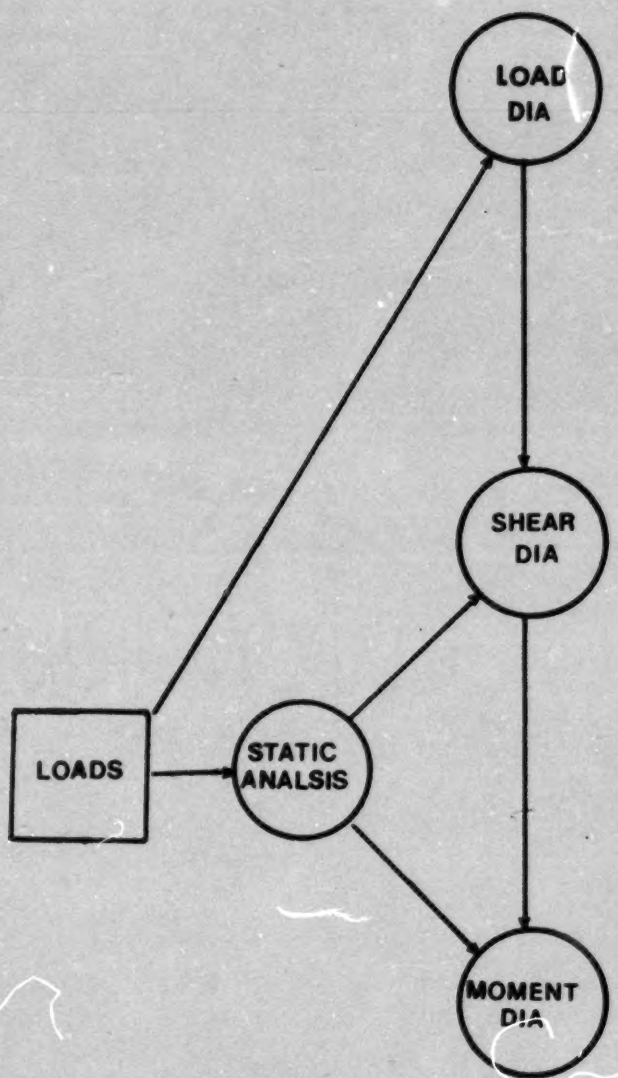

FIGURE 6.

"Given the loads on a beam, draw the load, shear, and moment diagrams." Each arrow on the graph means "provides information for." It represents in schematic terms the structure of the problem-solving method the student will use for a particular problem. A written description of what is occurring in the graph is:

> Take the loads on the beam and construct a load diagram. Also, take the loads and perform a static analysis on the beam. Integrate the load diagram to get the shear diagram, using a boundary condition given by the static analysis. Integrate the shear diagram to get the moment diagram, using a boundary condition from the static analysis.

The student responds by creating the graph showing his solution to the problem. (Figure 7).

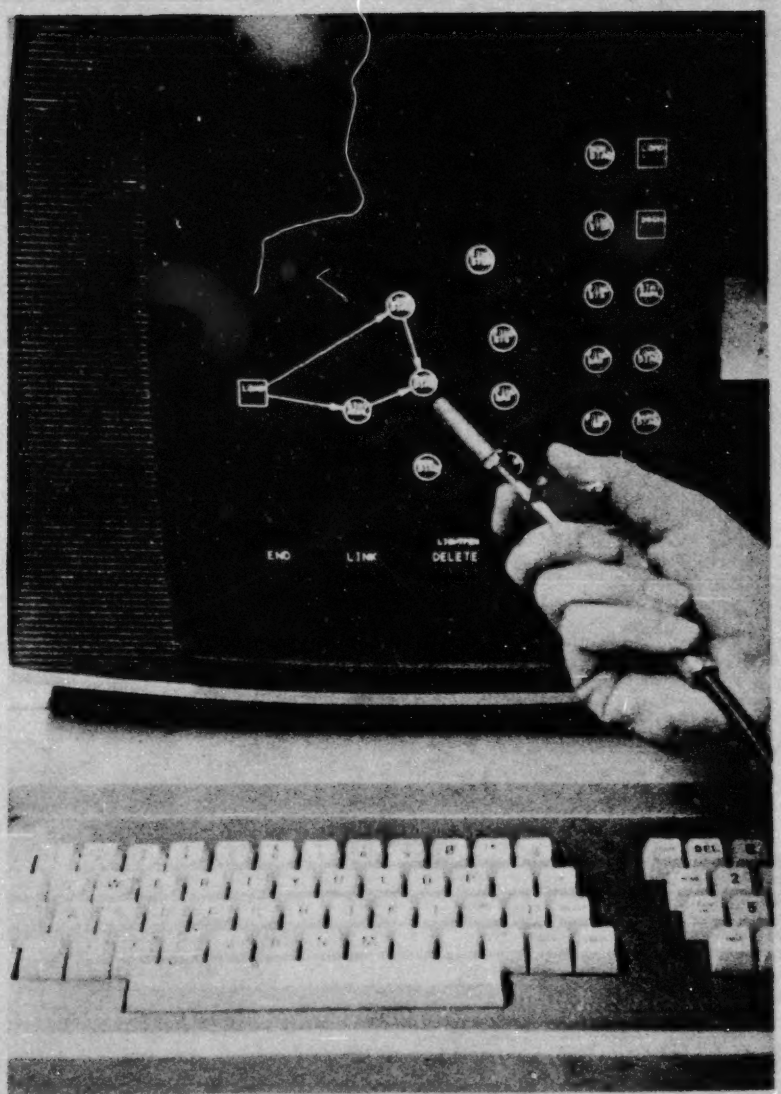

FIGURE 7

Conclusion.

This paper has discussed a program developed to detect and measure the communication of structure among known sets of options by the creation and editing of directing graphs. It represents the joint application of graph theory both as an internal data structure in the computer and as a display to the operator. Digraphs are not the only structural relationship possible, but are applicable to a large class of problems in the laboratory and the classroom. Since the development of these routines, they have found application in engineering design education, linguistics education, journalism education, and graph format for experimental investigations in man/machine communication. Evaluations of the approach are in progress in these areas.

Acknowledgements.

The authors would like to acknowledge the contributions of Mr. Tom Montemayor who encoded the programs on the NOVA-BASIC CBERT system.

This research was supported in part by Project C-BE under Grant GY-9340 "The Use of Computer-Based Teaching Techniques in Undergraduate Science and Engineering Education" from the National Science Foundation to The University of Texas at Austin, Drs. John J. Allan and J. J. Lagowski, Co-Directors.

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